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A CP Violation and Rare Kaon Decay Experiment at Fermilab*

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ABSTRACT

The E731 collaboration at Fermilab has collected enough $K \to 2\pi$ events to give a statistical error of $\approx 0.5 \times 10^{-3}$ on the CP violation parameter ε'/ε. Improvements have been made to reduce the systematic error. The experiment is also sensitive to many rare decays, and it set a new limit on the branching ratio of $K_L \to \pi^0 e^+ e^-$, $< 4.2 \times 10^{-8}$ (90%CL).

1. INTRODUCTION

It was about a quarter century ago, that CP violation was first observed in $K_L \to \pi^+\pi^-$ decay [1]. Nowadays, this $K_L \to \pi\pi$ decay is explained by the impurity of K_L, where a small mixture (ε) of the CP-even K_1 state in K_L decays into the CP-even $\pi\pi$ state. If this mixture is the only source of CP violation, then the decay amplitude of $K_L \to \pi^+\pi^-$ and $K_L \to \pi^0\pi^0$ would be the same [2]. On the other hand, if there is direct CP violation, where the CP-odd K_2 decays into the CP-even $\pi\pi$ state, then the two amplitudes would be different due to isospin. The size of the direct CP violation is represented by ε', and the ratio of amplitudes between K_L and K_S decays can be written:

$$\eta_{\pm} = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} = \varepsilon + \varepsilon' \tag{1}$$

$$\eta_{00} = \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} = \varepsilon - 2\varepsilon'. \tag{2}$$

The size of ε' can be measured by taking the double ratio :

$$\begin{aligned} \left|\frac{\eta_{\pm}}{\eta_{00}}\right|^2 &= \frac{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)} \\ &\approx 1 + 6\left|\frac{\varepsilon'}{\varepsilon}\right| \quad . \end{aligned} \tag{3}$$

As was mentioned by Dr. Buras in this conference[3], the standard model prediction for $|\varepsilon'/\varepsilon|$ ranges from 0.0007 to 0.007, while the superweak model predicts 0.0.

2. THE E731 EXPERIMENT AT FERMILAB

The goal of our experiment is to measure the double ratio (eq.3) with an error of 0.005, which corresponds to an error of 0.0008 for ε'/ε. In order to achieve this goal, one must have not only high statistics, but also a good control of systematic errors. The double ratio has to be insensitive to changes in beam flux, the accidental rate which suppresses good events, and efficiency and gain of the detector which may depend on the counting rate, radiation damage, or temperature.

In order to minimize the systematic error, E731 used two beams, one containing K_L and the other K_S (double beam technique). The K_L and K_S decays were detected by the same detector (because they were in the same final state) at the same time with the same trigger, and they both had the same effect from accidentals. The data of both decays were analyzed with the same calibrations and the same reconstruction cuts. The events were then divided into K_L and K_S samples by determining the beam in which they originated, and then they went through background and acceptance corrections separately. The merit of this double beam technique is that the effects of dead time, inefficiency of the detector, accidental losses, and beam flux do cancel to first order.

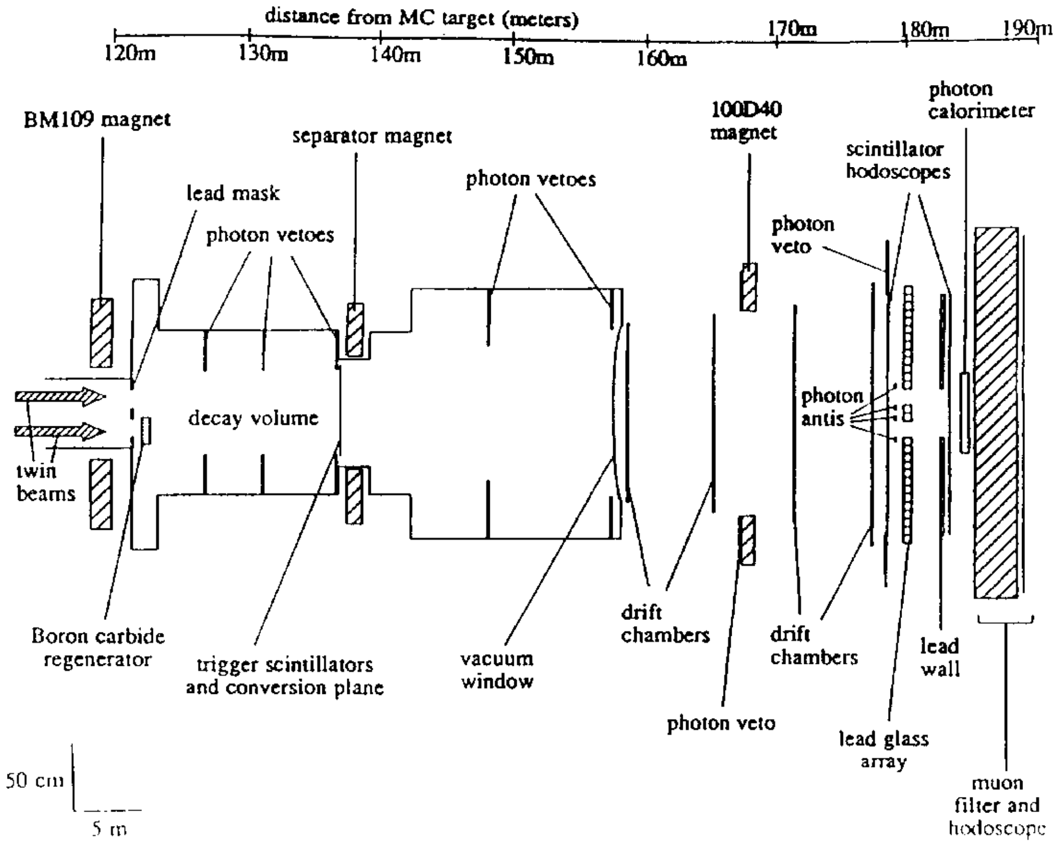

FIG.1. Detector Schematic, elevation view.

Figure 1 shows the detector layout. Two neutral K_L beams (1/2 x 1/2 mrad^2) were created at 4.8 mrad by 800 GeV protons striking a Be target. One of the two beams always hit a regenerator to create K_S. The regenerator consisted of 4 modules of 19.4cm B_4C blocks, each of which was followed by scintillators to veto inelastic regeneration. The regenerator was moved between the two beams for every spill (every minute) to cancel any possible asymmetry of the beams or the detector. The drift chamber system with eight x-planes and eight y-planes (2000 wires total) measured the positions and momenta of the charged particles. These planes had a position resolution of about 100μm and were at least 98% efficient. The 804 circularly stacked lead glass blocks measured the positions and energies of electrons and photons. Each block is 5.82cm(H) x 5.82cm(W) x 60.2cm (L), giving a depth of 19.2 radiation lengths. The position and energy resolution for electrons were about 2mm and

$1.5\% + 5\%/\sqrt{E(\mathrm{GeV})}$ respectively. Each of the lead glass phototube outputs were instrumented with a 60 MHz flash ADC to feed a hit pattern into a two-dimensional cluster finding trigger processor, and to suppress out-of-time photons. Two holes (11.6cm x 11.6cm) separated vertically by 11.6cm at the center of the lead glass array allowed the beams to pass through the detector. A photon calorimeter with 48 layers of lead and lucite, giving 28.1 radiation lengths in total, was placed downstream of the lead glass to detect photons which passed through the holes. There were ten planes of photon detectors placed strategically to veto photons which escaped outside of the apparatus.

The signals were digitized by FASTBUS ADC's and CAMAC TDC's and sent to FASTBUS memory modules to reduce the dead time. The data were written to tape using a PDP11 computer; also a subsample was sent to a μVAX computer for online monitoring. Using a mainframe computer offline, one or two tapes in every eight hours were analyzed to further check the detector performance and the kaon yield.

In 1985, E731 collected 6747 $K_L \to \pi^0\pi^0$ events, yielding the measurement $|\varepsilon'/\varepsilon| = 0.0032 \pm 0.0028(\text{statistics}) \pm 0.0012$ (systematic) [4]. In 1987-1988, E731 successfully finished its final data taking run, collecting about 300k $K_L \to \pi^0\pi^0$ events and 400k $K_L \to \pi^+\pi^-$ events. The number of K_S events was about three times that of the K_L events. The data we present here represent 20% of the total sample, which were taken triggering on $\pi^+\pi^-$ and $\pi^0\pi^0$ modes simultaneously. These data were reduced using Fermilab's microcomputer farm (ACP).

3. CHARGED MODE

The charged mode ($K \to \pi^+\pi^-$) trigger required two tracks at the second drift chamber and at the scintillator hodoscope just upstream of the lead glass. The muon hodoscope after 3m of iron was used to veto $K_{\mu 3}$ events. In the offline analysis, K_{e3} events were rejected by requiring $E/p < 0.85$, where E is the energy measured by the lead glass, and p is the track momentum measured by the spectrometer.

Figure 2 shows the mass of $\pi^+\pi^-$ for K_S and K_L beams. The mass resolution (σ) is 3.4 MeV/c^2. The line shows the data and the dots show Monte Carlo events. For both beams, the discrepancy between data and Monte Carlo at the lower side of the peak is due to the $\pi^+\pi^-\gamma$ radiative decay. The discrepancy at the higher side of the K_L peak is due to K_{e3} decays. The background due to $K_L \to \pi^+\pi^-\pi^0$ is suppressed to a negligible level by the good mass resolution.

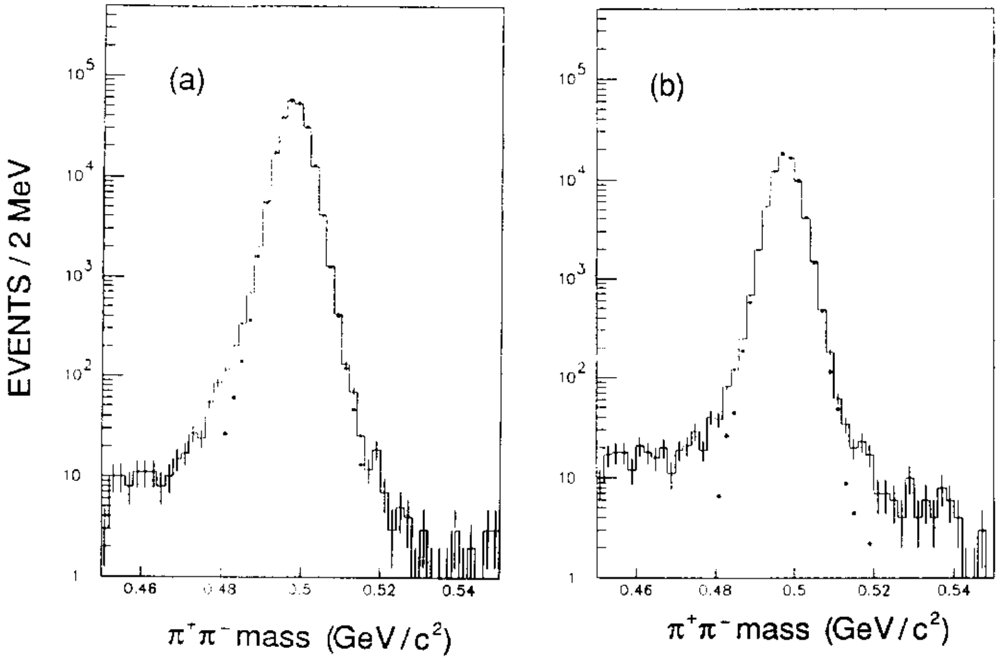

FIG. 2. Reconstructed $\pi^+\pi^-$ mass for K_S (a) and K_L (b).

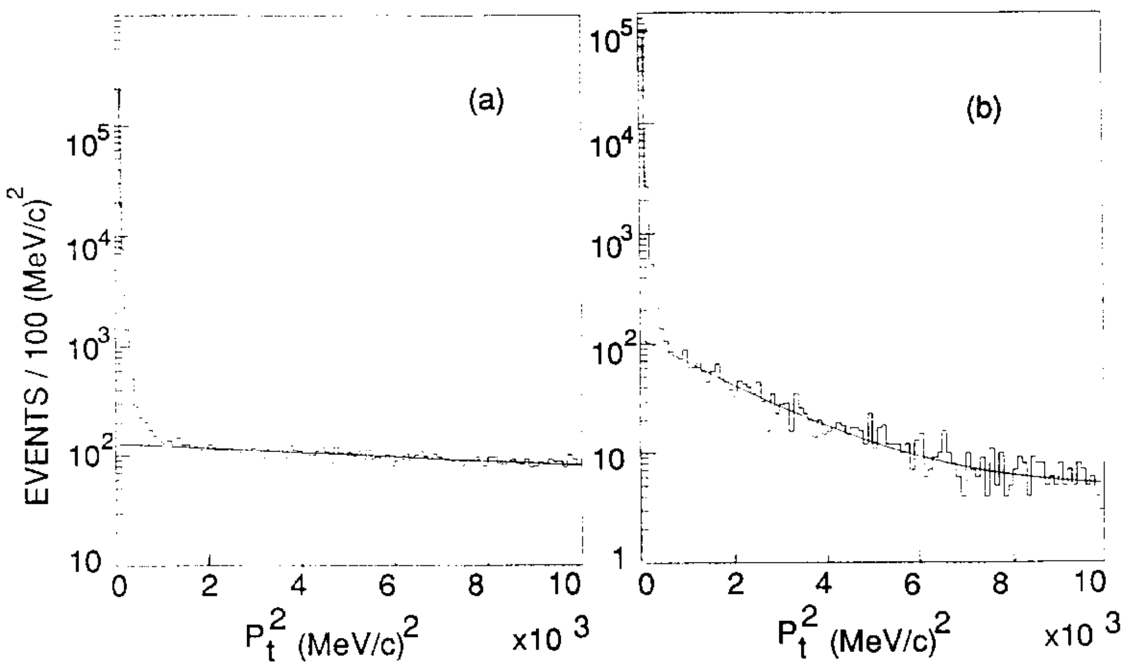

FIG. 3. P_t2 of $\pi^+\pi^-$ system for K_S (a) and K_L (b).

Figure 3 shows the square of the transverse momentum (P_t2) of the $\pi^+\pi^-$ system with respect to the line connecting the production target and the kaon position at the regenerator. The peak at 0 in Fig.3.a is K_S made by coherent regeneration, and the tail is K_S from diffractive and inelastic regeneration. The background under the peak (<250 MeV^2/c^2) is 0.14%. Compared to the 1985 run, the background was reduced by a factor of 2, by removing lead pieces from the regenerator which enhanced the diffractive background. The peak in Fig.3.b is the $K_L \to \pi^+\pi^-$ signal, while the tail comes mostly from K_{e3} events. The $K_{\mu 3}$ background is negligible because of an efficient muon hodoscope. The background under the peak (<250 MeV^2/c^2) is 0.37%, and this was reduced by a factor of 3.3 compared to the 1985 run due to the improvements made in the muon hodoscope.

One of the interesting backgrounds is the $K_{S,L} \to \pi^+\pi^-\gamma$ decay. There are two kinds of radiative decay; inner bremsstrahlung and direct emission. The inner bremsstrahlung comes from a virtual pion in the decay, so the final CP is even (+1). Since this radiation is common to both K_S and K_L decays, it does not affect $\eta_{\pm}$ even if the events are included in the signal region. On the other hand, the photon from the direct emission comes from the $K\pi\pi$ vertex, so the final CP is odd (-1). Therefore the direct emission is allowed by CP in K_L decay while it is suppressed in K_S decay, and this could change $\eta_{\pm}$. We have seen the $\pi^+\pi^-\gamma$ signal, and as will be described, the effect on $\eta_{\pm}$ is negligible in our experiment.

The sample of $\pi^+\pi^-\gamma$ events was selected by requiring two tracks and one photon cluster in the glass. Figure 4 shows the mass of the $\pi^+\pi^-\gamma$ system and we see a clear peak at the kaon mass for both K_S and K_L. The bump at around 440MeV/c^2 in the K_L sample is due to $K_L \to \pi^+\pi^-\pi^0$ events with one missing photon. The energy of the radiative gamma in the center of mass frame is shown in Fig. 5. The K_S has the typical 1/k spectrum of inner bremsstrahlung, while the K_L shows a broad distribution around 80MeV in addition to the inner brem spectrum. The bump is from CP-allowed direct emission, and it falls off near 0. For $\pi^+\pi^-$ analysis, we can apply a tight cut on the kaon mass because of the excellent resolution of the drift chamber spectrometer. The mass cut of 484-512MeV/c^2, which corresponds to <15MeV for radiative gamma energy, and the P_t2 < 250MeV^2/c^2 cut, eliminate most of the $\pi^+\pi^-\gamma$ events from direct emission. A Monte Carlo study found that only one event from direct emission is expected in our total $K_L \to \pi^+\pi^-$ sample, and the effect on ε'/ε is only 4 x 10^{-7}.

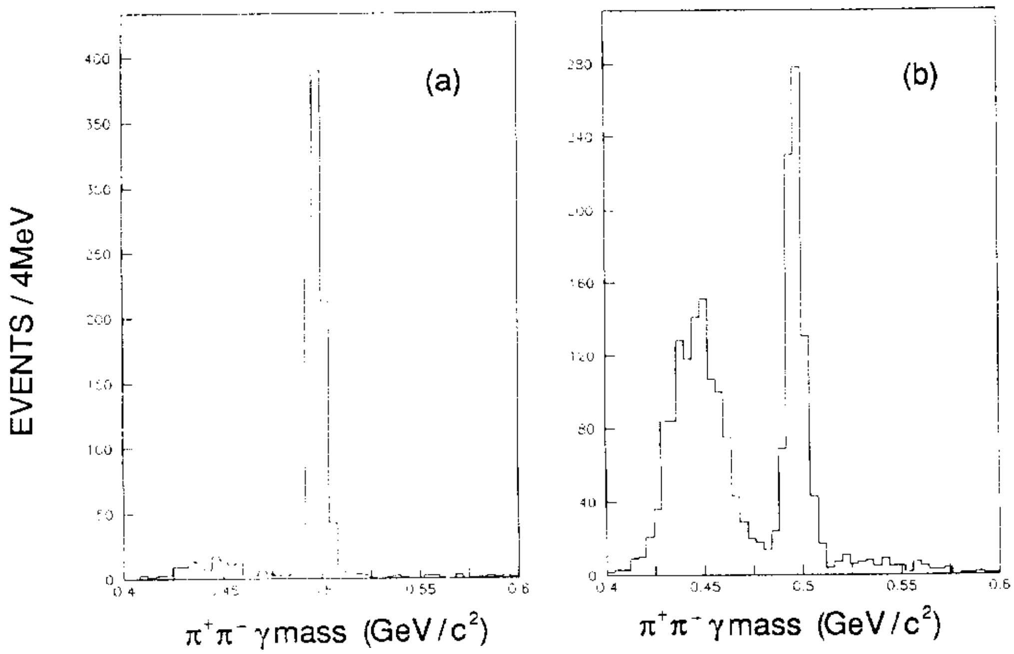

FIG. 4. $\pi^+\pi^-\gamma$ mass of K_S (a) and K_L(b).

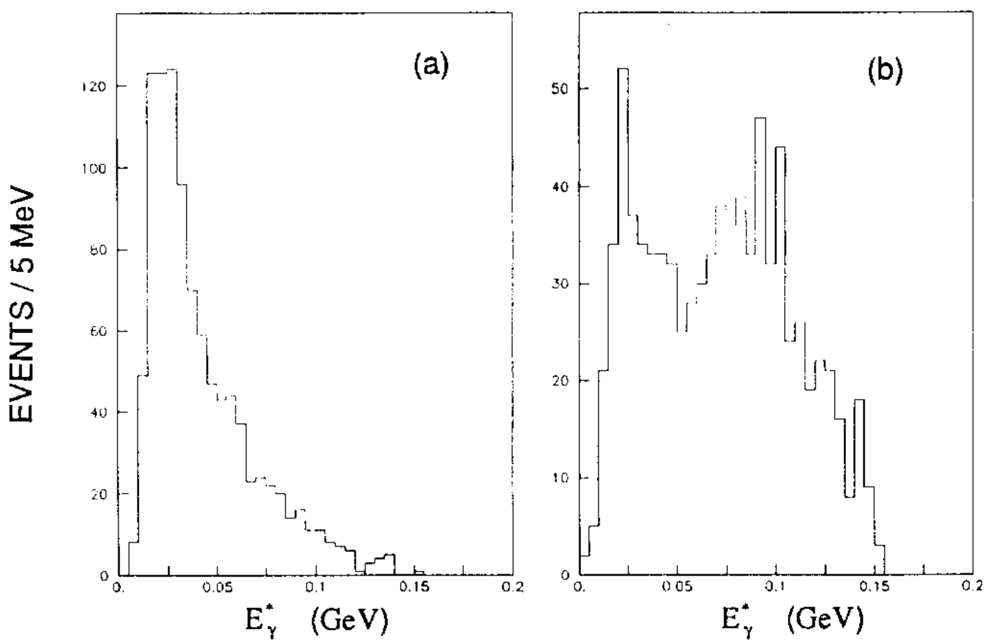

FIG.5. Energy of radiative photon in the center of mass frame for K_S(a) and K_L(b).

4. NEUTRAL MODE

In the neutral mode, the lead glass was used to reconstruct the decay z vertex and the kaon mass. Since the understanding of the lead glass energy scale is very important, we had several ways to check the gain and to study its response.

The lead glass was calibrated every 2-3 weeks by using electron pairs converted from a photon beam. As shown in Fig.6.a, the sample was background free and the width of E/p was 3.1% (σ). Between electron calibrations, the gain of the glass was tracked by using a Xe flasher light, which was distributed every second to all the blocks through glass fibers. During the run, $K_L \to \pi^+\pi^-\pi^0$ events were recorded simultaneously. This sample is useful for studying the photon response of the lead glass, because the decay vertex of the π^0 is known from the charged pion tracks. The mass of reconstructed π^0 from $\pi^+\pi^-\pi^0$ sample is shown in Fig. 6.b; and the mass resolution is 3.7MeV/c^2. In order to check the acceptance for the neutral mode, $K_L \to \pi^0\pi^0\pi^0$ events were also taken simultaneously. Figure 7 shows the decay vertex distribution for the $3\pi^0$ sample. The data and Monte Carlo match well, but it will be further improved after the calibration and the resolution study is finished.

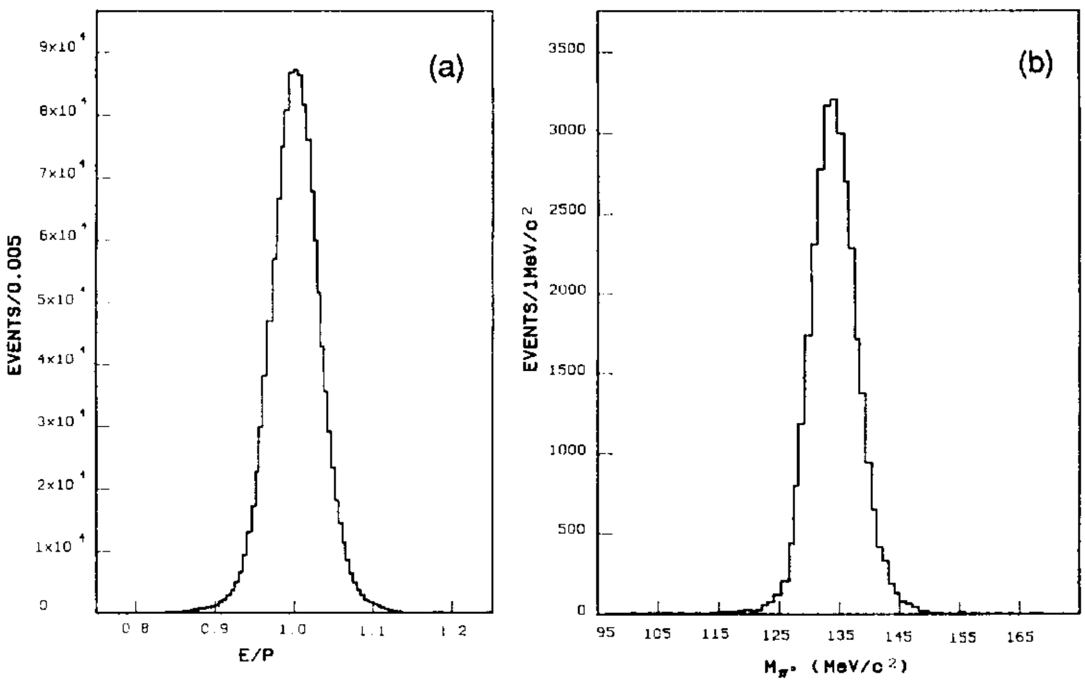

FIG.6. (a) E/p in the lead glass from the electron calibration data. (b) Reconstructed π^0 mass from $K_L \to \pi^+\pi^-\pi^0$ decays.

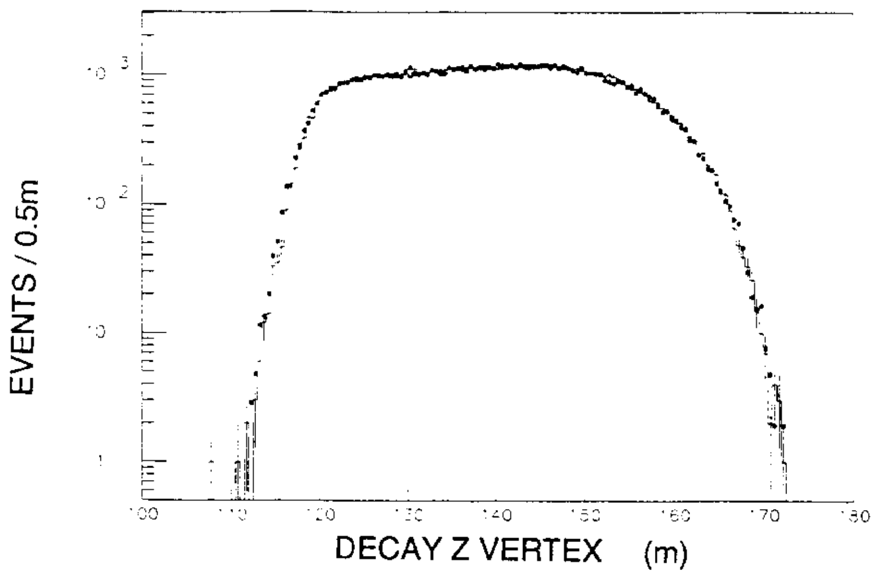

FIG.7. Decay vertex from $3\pi^0$ sample.

The neutral mode ($K_{S,L} \rightarrow \pi^0\pi^0$) trigger required 4 photon clusters and 30GeV or more total energy deposited in the lead glass array. A cluster was defined as a neighbor-connected island of lead glass blocks each with more than 1GeV.

In the offline analysis, the ten planes of photon veto counters were used to reduce the background from $K_L \rightarrow \pi^0\pi^0\pi^0$ events where two out of six photons did not hit the lead glass or overlapped with another photon, and faked 4 clusters. The reduction factor was checked to be the same for both K_L and $K_S \rightarrow \pi^0\pi^0$ samples. The K_L and K_S samples were separated by the center of gravity of energies at the glass (extrapolated position of kaon at the glass), as shown in Fig. 8. Figure 9 shows the reconstructed $\pi^0\pi^0$ mass distribution. The background in the K_S sample comes from the remaining $K_L \rightarrow \pi^0\pi^0\pi^0$ events, where the K_L did not interact in the regenerator. The background is only 0.02% under the K_S mass peak. The $3\pi^0$ background in the $K_L \rightarrow \pi^0\pi^0$ sample is 0.3%; it has been reduced by a factor of 5 from 1985 run, due to the improved photon veto counters and offline cuts to reject photon overlaps.

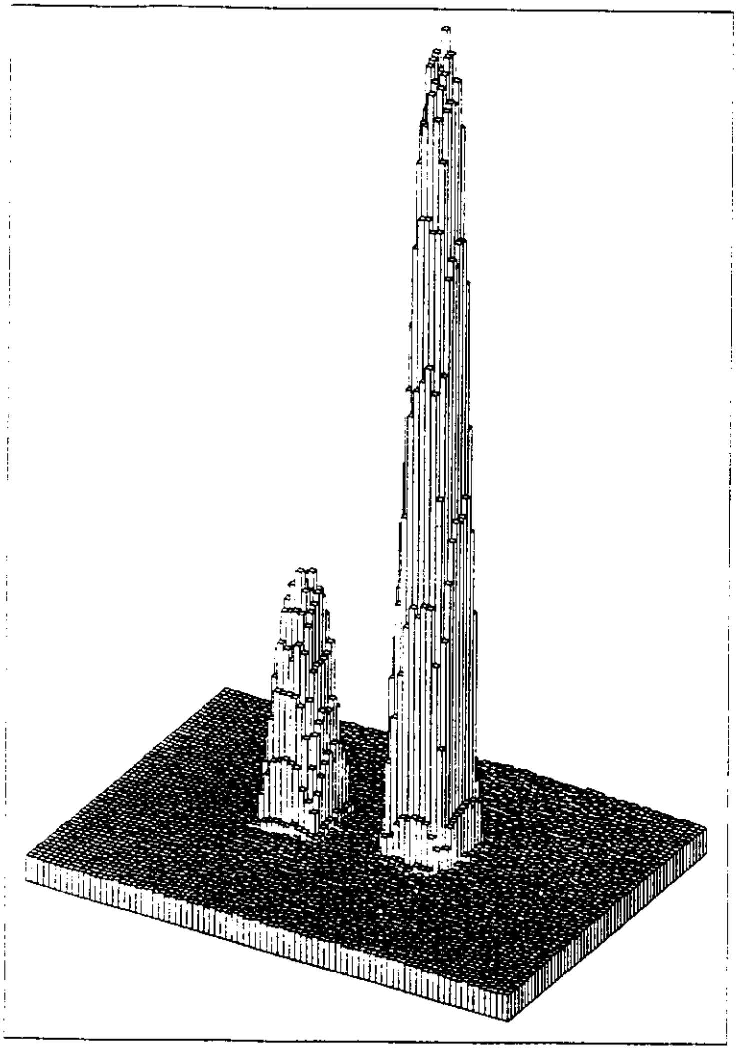

FIG.8. Center of energy distribution at the lead glass array. The right (left) hand side tower corresponds to regenerator (vacuum) beam.

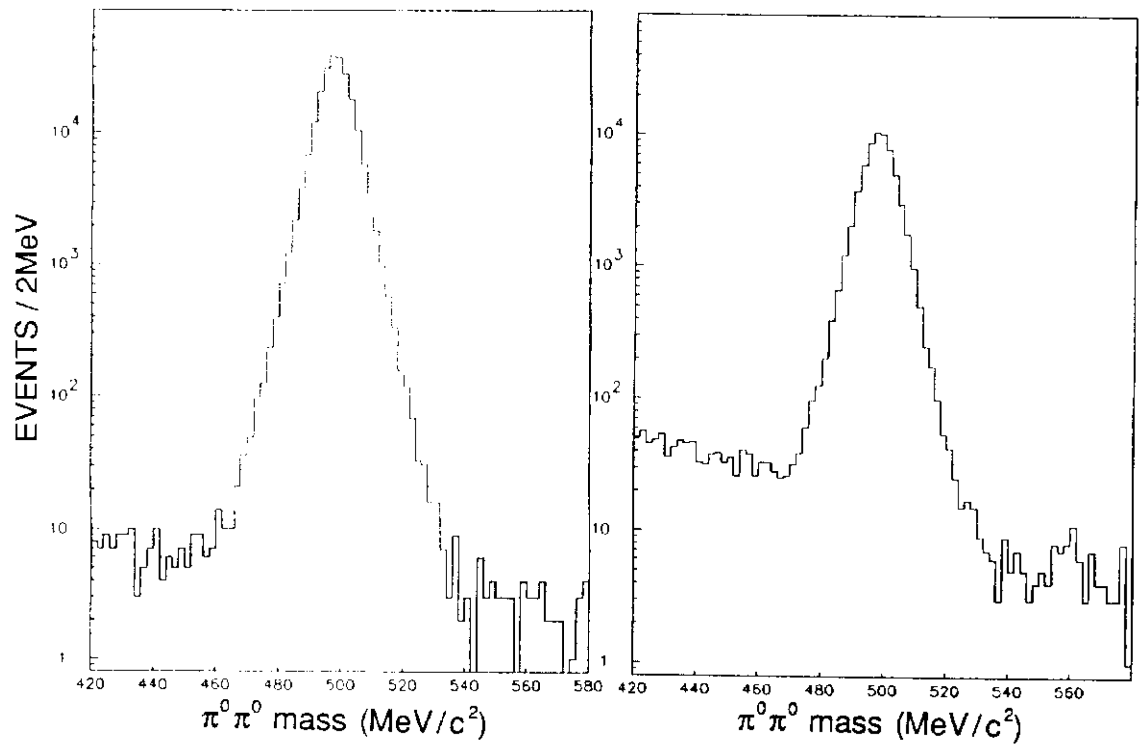

FIG.9. $\pi^0\pi^0$ mass for K_S (a) and K_L (b).

The other background in neutral mode is K_S from diffractive and inelastic regeneration. These events will make backgrounds not only for K_S, but also for K_L by crossing between the two beams. Unlike the charged mode or neutral mode in the 1985 run [4] in which we converted one of the photons, we do not have P_t2 information to eliminate these backgrounds. However, the background level is understood very well by the following method.

First, we obtained the acceptance-corrected P_t2 distribution from the charged mode (Fig.10), and fit it by a sum of two exponentials. In Fig.10, the steeper slope near 0 is due to diffractive regeneration and the rest is due to inelastic regeneration. We then plugged the P_t2 distribution into the neutral mode Monte Carlo, and looked at the center of energy distribution. The shape of the beams was determined very well from charged mode, by taking into account all the beam line elements in the Monte Carlo, as shown in Fig. 11. The reconstructed events were binned by square rings, where the rings start from the center of the beam and each ring covers the same area. Figure 12 shows the rings around the regenerator and vacuum beams. The lines are data and the crosses are Monte Carlo. The height of Monte Carlo points are normalized by the number of coherent K_S in the data. The shape and the level of the background agrees very well in both beams, and the background levels are 2.44±0.05% for K_S and 3.87±0.11% for

K_L. The errors come mostly from Monte Carlo statistics.

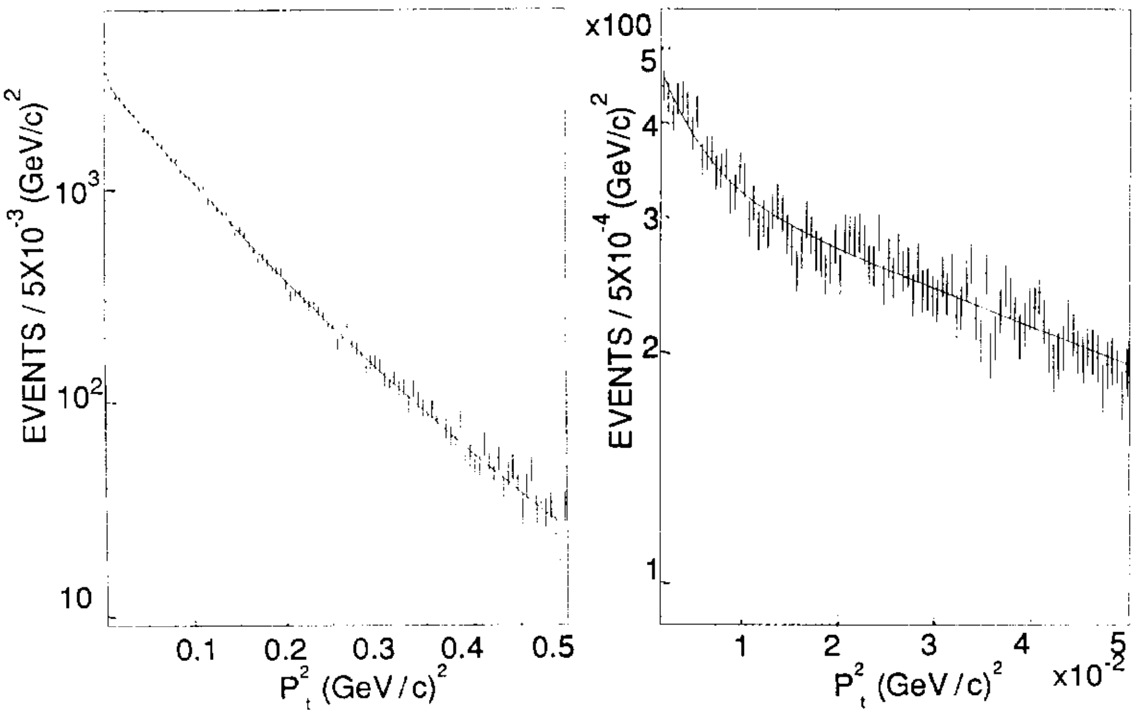

FIG.10. P_t2 distribution of the non-coherent $K_S \rightarrow \pi^+\pi^-$ events. The right hand side plot is a close view of near 0.0.

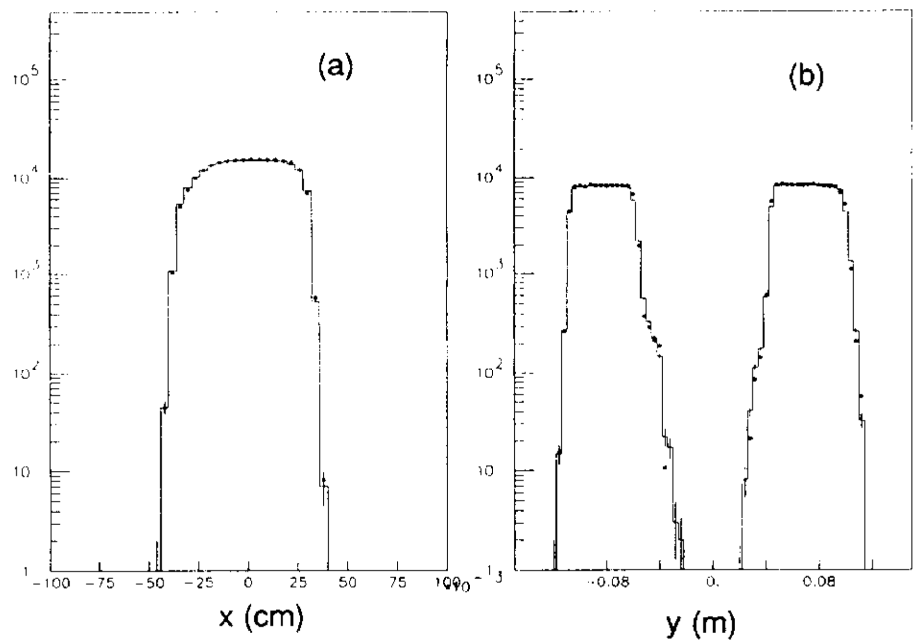

FIG. 11. Beam shape from charged mode data; (a) horizontal view and (b) vertical view.

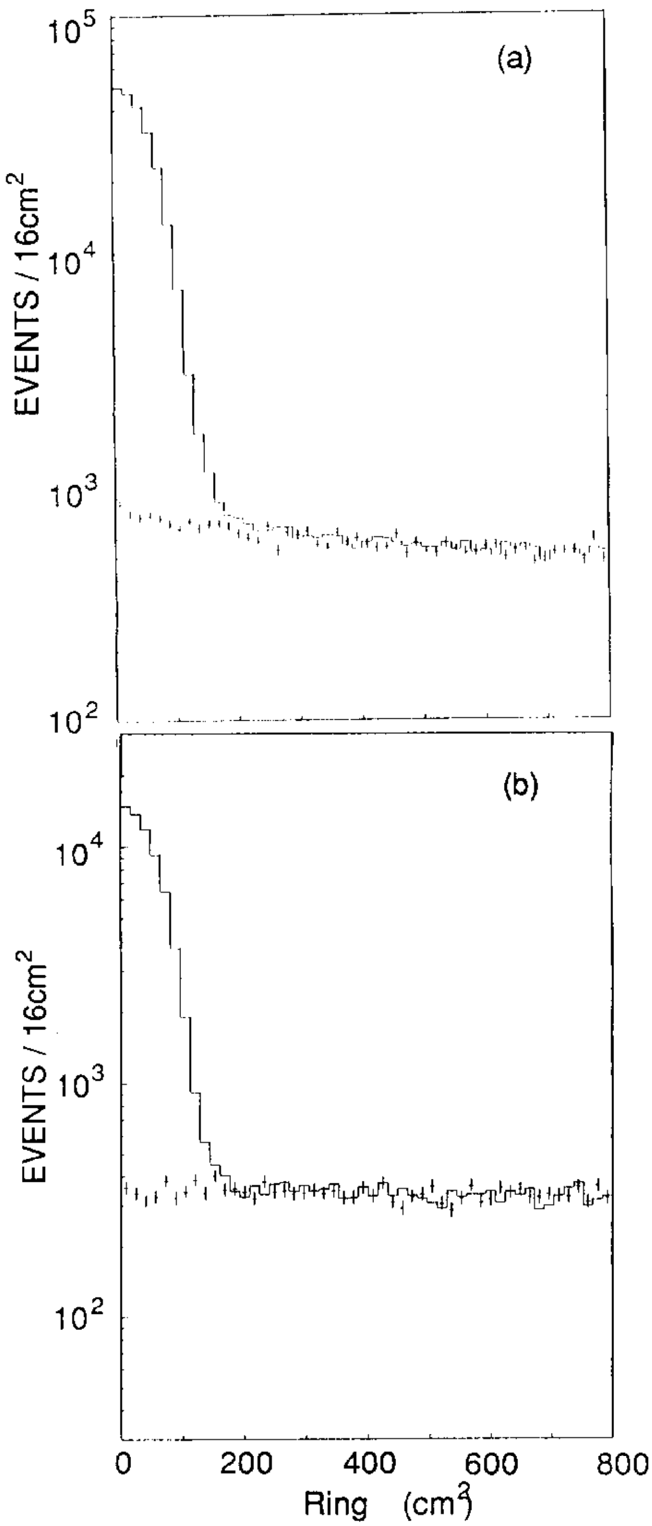

FIG.12. Center of energy distribution in rings for K_S (a) and K_L (b). The horizontal axis is the inside area of the square (cm^2).

5. SYSTEMATIC ERRORS

We are not at the stage of estimating the systematic errors, but we have made many improvements from the 1985 run to reduce the systematic errors.

i) Background Subtraction

The 1985 run had a systematic error of 0.40% in the double ratio due to the uncertainty in the background subtraction.. As summarized in Table 1, all the background levels have been reduced in the 1988 run, and this should reduce the systematic error accordingly.

Table 1. Background comparison between 1985 and 1988 run.

Decay mode	Background source	Background level (%) 1985 run	1988 run
$K_L \to \pi^+\pi^-$	K_{e3}	1.23±0.18	0.37
$K_S \to \pi^+\pi^-$	diffractive+inelastic regeneration	0.30±0.03	0.14
$K_L \to \pi^0\pi^0$	$3\pi^0$	1.56±0.30	0.3
	diffractive+inelastic regeneration		3.87±0.1
$K_S \to \pi^0\pi^0$	$3\pi^0$	2.90±0.20	2.4
	diffractive+inelastic regeneration		2.44±0.05

ii) Accidentals

Although the event losses due to accidentals are the same for both K_L and K_S to first order, it could be different in second order because the distribution of photons in the lead glass for K_L and K_S are not exactly the same and the accidental hits are not perfectly uniform. In the 1985 run, the systematic error due to accidentals was 0.2% in the double ratio.

In order to study this effect, we introduced an 'accidental trigger' in the 1987-1988 run. This trigger was made by a coincidence of two scintillation counters aiming at the production target to make the trigger rate proportional to the instantaneous proton intensity. All the detectors were read out exactly the same as for the other triggers. The accidental data will be superimposed on Monte Carlo data to check the effect of accidentals.

Improvements were also made on lead glass signals. We reduced the integration time from 250ns (1985 run) to 150ns (1987-1988 run) and used 60MHz flash ADC's to discriminate the peak pulse height at 1GeV. This helped to reduce the event loss due to out-of-time accidentals in the neutral mode.

iii) Neutral Mode Energy Scale

In the 1985 run, the systematic error due to the uncertainty in the lead glass energy scale was 0.21% in the double ratio. In the 1987-1988 run, in addition to 7.7M e^+e^- pairs from calibration, we have about 80M electrons from K_{e3} decays, and 2M $K \rightarrow \pi^+\pi^-\pi^0$ events. These rich samples should help us to understand the behavior of the lead glass in more detail and to reduce the systematic error.

iv) Charged Mode Acceptance.

The systematic error due to uncertainty in the charged mode acceptance was 0.25% in double ratio in the 1985 run. In the 1987-1988 run, the number of $K_L \rightarrow \pi^+\pi^-$ events was increased from 36k to 400k, and this should help us to study data and Monte Carlo difference in more detail and reduce the uncertainty.

v) Neutral Mode Acceptance

In the 1985 run, the uncertainty in the neutral mode acceptance correction was 0.50%. In the 1987-1988 run, we took about 10M $K_L \rightarrow \pi^0\pi^0\pi^0$ events, compared to 0.5M in the 1985 run. This will be useful to check the neutral mode acceptance in more detail.

The total systematic error on the double ratio in the 1985 run was 0.75%, which corresponded to 0.0012 in ε'/ε. With all these improvements described above, we should be able to reduce the systematic error to a level comparable to the statistical error of 0.0005 in ε'/ε.

6. OTHER PHYSICS (RARE KAON DECAYS)

Many other physics results can be obtained from our data sample, including the phase difference between $\eta_{\pm}$ and η_{00}, the charge asymmetry in K_{e3} which measures the real part of ε, and some rare kaon decays which will be described here.

6.1 $\pi^0 \to e^+e^-$

The $\pi^0 \to e^+e^-$ decay can be described by a fourth-order electromagnetic box diagram, and the branching ratio is calculated[5] to be $>4.8\times10^{-8}$. The published branching ratio of $(1.8\pm0.7)\times10^{-7}$ comes from two measurements [6,7], but there is a mild controversy on the validity of the results. E731 used a new technique to measure the branching ratio, which tags π^0 by using $K_L \to \pi^0\pi^0\pi^0$ decays. The signature of $\pi^0 \to e^+e^-$ is six clusters in the glass with two tracks matched with clusters and reconstructed as a π^0, the four other clusters reconstructed as two π^0, and all three π^0 reconstructed as a kaon coming from the production target. Figure 13 shows the scatter plot of kaon mass vs e^+e^- mass, and the box corresponds to the 90% confidence region. There is no background and the preliminary limit is B.R.$(\pi^0 \to e^+e^-) < 2.5\times10^{-7}$ (90% confidence).

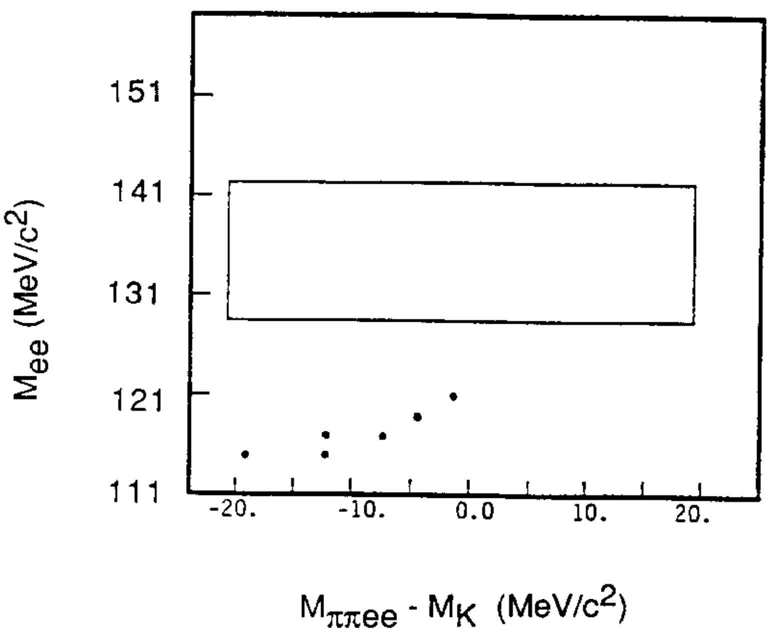

FIG.13. Reconstructed kaon mass vs e^+e^- mass for the six cluster and two track data. The box represents 90% confidence signal region for $\pi^0 \to e^+e^-$.

6.2 $K_L \rightarrow e^+e^-\gamma$

Only 4 K_L Dalitz decay events have been observed so far [8], and the published branching ratio is $(1.7\pm0.9)\times10^{-5}$. We have seen 12 events in the 20% of the total sample. Figure 14 shows the scatter plot of e^+e^- mass vs $e^+e^-\gamma$ mass. The kaon mass resolution is about $8\mathrm{MeV/c^2}$ and there is a clear separation between the Dalitz decay signal and the low $M_{ee\gamma}$ events from radiative K_{e3}. The preliminary branching ratio is $(1.4\pm0.4)\times10^{-5}$, which is consistent with the current number.

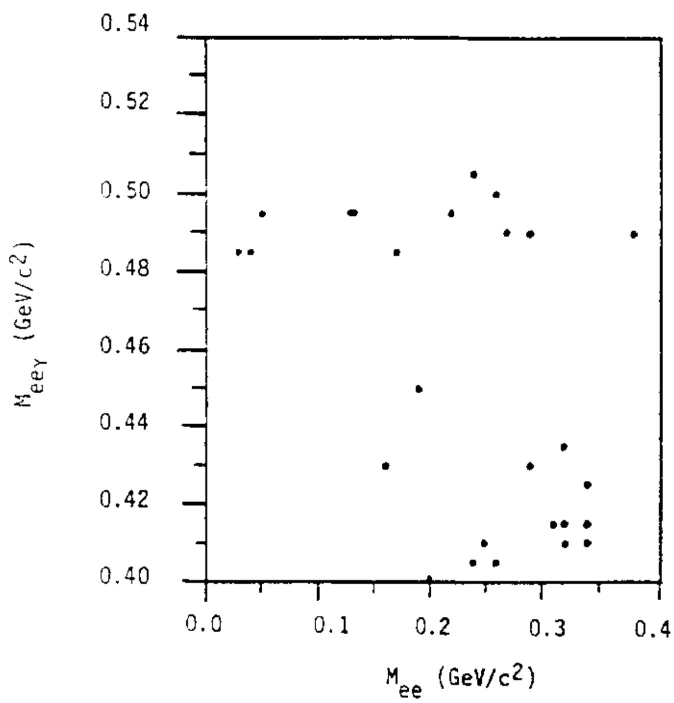

FIG.14. e^+e^- mass vs $e^+e^-\gamma$ mass of K_L Dalitz decay.

6.3 $K_L \rightarrow \pi^0 e^+e^-$

The $K_L \rightarrow \pi^0 e^+e^-$ decay is interesting because it is expected to have a sizable direct CP violating effect ($\varepsilon'/\varepsilon \approx 1$) [9]. The predicted branching ratios are around 10^{-11}. The signature of this decay was four clusters with two clusters associated with tracks giving $0.85<E/p<1.15$, and the other two clusters formed a π^0 mass. Figure 15 shows the scatter plot of reconstructed kaon mass ($m_{\pi ee}$) vs P_t2 of the $\pi^0e^+e^-$ system. The resolution of $m_{\pi ee}$ and p_t2 are about $4.5\mathrm{MeV/c^2}$ and $50(\mathrm{MeV/c})^2$ respectively. The box in the figure includes about 95% of the signal region. Having no events within the box, the upper limit B.R.($K_L \rightarrow \pi^0 e^+e^-$) $< 4.2\times10^{-8}$ (90% confidence) is obtained[10]. The result will be improved by a factor of 5 by analyzing our total data sample.

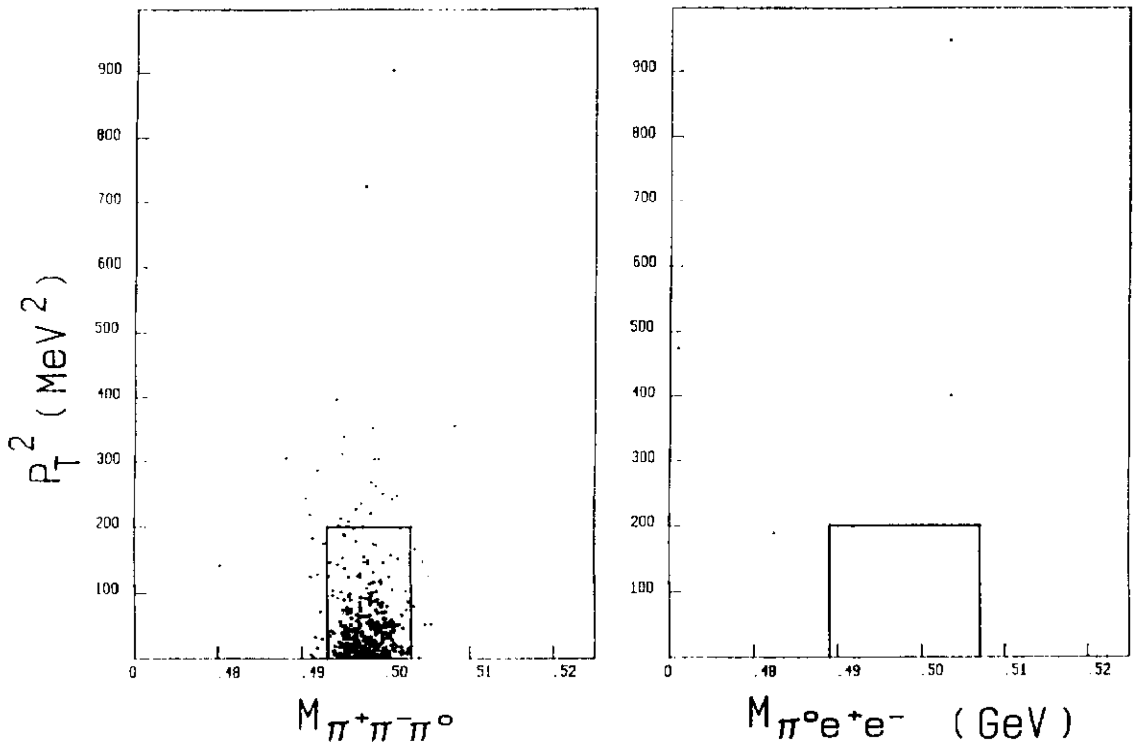

FIG.15. Reconstructed kaon mass vs the square of the transverse momentum for (a) $K_L \rightarrow \pi^+\pi^-\pi^0$ and (b) $\rightarrow \pi^0 e^+ e^-$. The events in the plots were selected with a π^0 mass cut of 2.5σ and the boxes represent the signal region.

7. SUMMARY

We have collected enough data to give statistical error of 0.0005 in ε'/ε, and we expect to have the comparable size of systematic error. We are currently improving the lead glass gains, and studying the acceptance and backgrounds. We plan to obtain the result from 20% of the total sample by the spring of 1989, and present the final result from the total data sample within a year.

In 1990, E773 will run by modifying some of the apparatus to measure the phase difference between $\eta_{\pm}$ and η_{00} with an accuracy of 0.5 degree. We have also proposed a new experiment (P799) to measure the branching ratio of $K_L \rightarrow \pi^0 e^+ e^-$ with a sensitivity of 1×10^{-11}, which will open a new gate to observe direct CP violation.

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